

The rare decay $B_c \rightarrow D_s^* \mu^+ \mu^-$ in a family non-universal Z' model

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Abstract

Using the form factors calculated in the three-point QCD sum rules, we calculate the new physics contributions to the physical observables of $B_c \rightarrow D_s^* \mu^+ \mu^-$ decay in a family non-universal Z' model. Under the consideration of three cases of the new physics parameters, we find that: (a) the Z' boson can provide large contributions to the differential decay rates; (b) the forward-backward asymmetry (FBA) can be increased by about 47%, 38%, and 110% at most in S1, S2, and extreme limit values (ELV), respectively. In addition, the zero crossing can be shifted in all the cases; (c) when $\hat{s} > 0.08$, the value of P_L can be changed from -1 in the Standard Model (SM) to -0.5 in S1, -0.6 in S2, and 0 in extreme limit values, respectively; (d) the new physics corrections to P_T will decrease the SM prediction about 25% for the cases of S1 and S2, 100% for the case of ELV.

Key words: Rare decays, Standard Model, a family non-universal Z' model

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I. INTRODUCTION

The Standard Model (SM) of interactions among elementary particles is one of the best verified physics theories up to now but there are many open fundamental questions remain unanswered within the scope of the SM. High energy physics experiments are designed to address the open questions through the search of new physics (NP) using two complementary approaches. One is to discover the new particles at the high energy Large Hadron Collider (LHC). The other is to search for the effects of NP through measurements of flavor physics reactions at lower energy scales and evidence of a deviation from the SM prediction.

After the observation of the rare radiative decay $b \rightarrow s\gamma$ [1], the flavor-changing neutral current (FCNC) transitions became more attractive and since then many works about rare radiative, leptonic and semileptonic decays have been intensively done in the $B_{u,d,s}$ system [2]. Among these decays, semileptonic decay channels are significant because their branching ratios are relatively larger. These works will be more perfect if similar studies for B_c , observed in 1998 by CDF Collaboration [3], are also included.

The charmed B_c meson is a ground state of two heavy quarks b and c . Because of the two heavy quarks, the decays of the B_c meson are rather different from $B_u/B_d/B_s$ mesons. Physicists therefore believe that the B_c physics must be very rich compared to the other B mesons if the statistics reaches high level [3–5]. At LHC, around 5×10^{10} B_c events per year are expected [6, 7]. The expected number events are motivating to work on the B_c phenomenology and this possibility will provide facilities to study the observables of rare B_c decays such as branching ratios, forward-backward asymmetry and polarization asymmetries.

The rare $B_c \rightarrow D_s^* l^+ l^-$ decays are proceeded by FCNC transition of $b \rightarrow sl^+ l^-$, which are forbidden at the tree level in the SM, and play an important role in the precision test of the SM. Meanwhile, they offer a valuable possibility of an indirect search of NP for their sensitivity to the gauge structure and new contributions. Up to now, the possible new physics contributions to $B_c \rightarrow D_s^* l^+ l^-$ decays have been studied extensively, for example, by using model independent effective Hamiltonian [8], in Supersymmetric models [9], with fourth generation effects [10], and in single universal extra dimension [11].

When concentrating on the exclusive $B_c \rightarrow D_s^* l^+ l^-$ decays, one needs to know the form factors. As for $B_c \rightarrow D_s^*$ transition, the form factors have been calculated using different approaches, such as light front constituent quark models [12], a relativistic constituent quark model [13], a relativistic quark model [14], the Ward identities [15], in light cone QCD [16, 17], and QCD sum rules [18–20]. In this work, we will adopt the form factors calculated in the three-point QCD sum rules [20] to study the Z' effects on the observables for $B_c \rightarrow D_s^* \mu^+ \mu^-$ decay.

The general framework for non-universal Z' model has been developed in Ref. [21]. In

this model, Z' gauge boson could be naturally derived by adding additional $U(1)'$ gauge symmetry. Non-universal Z' couplings can induce FCNC $b \rightarrow s$ and d transitions at tree level. Its effects on $b \rightarrow s$ transition have received great attention and been widely studied in the literature. The previous works in a family non-universal Z' model boson redound to resolve many puzzles, such as " πK puzzle" [22, 23], anomalous $\bar{B}_s - B_s$ mixing phase [24, 25] and mismatch in $A_{FB}(B \rightarrow K^* \mu^+ \mu^-)$ spectrum at low q^2 region [26, 27]. Motivated by this, we will study the effects of the Z' boson on the rare decay $B_c \rightarrow D_s^* \mu^+ \mu^-$.

This paper is organized as follows. In Section 2, we present the effective Hamiltonian responsible for the $b \rightarrow sl^+l^-$ transition in both the SM and the family non-universal Z' model. In this section we also present the matrix element, and the expressions of various physical observables in Z' model. In Section 3, we show the numerical results of the observables for $B_c \rightarrow D_s^* \mu^+ \mu^-$ decay in the SM and Z' model. The final section is the summary.

II. EFFECTIVE HAMILTONIAN, MATRIX ELEMENTS AND OBSERVABLES FOR $b \rightarrow sl^+l^-$ DECAY

At quark level, the rare semileptonic decay $b \rightarrow sl^+l^-$ can be described in terms of the effective Hamiltonian which is given by [28, 29]

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) O_i(\mu). \quad (1)$$

here the explicit expressions of O_i can be found in Ref. [28], in which

$$O_9 = \frac{e^2}{g_s^2} (\bar{d} \gamma_\mu P_L b) (\bar{l} \gamma^\mu l), \quad O_{10} = \frac{e^2}{g_s^2} (\bar{d} \gamma_\mu P_L b) (\bar{l} \gamma^\mu \gamma_5 l). \quad (2)$$

The Wilson coefficients C_i can be expanded perturbatively [30–33]. The effective coefficients $C_{7,9}^{\text{eff}}$, can be written as [28]

$$\begin{aligned} C_7^{\text{eff}} &= \frac{4\pi}{\alpha_s} C_7 - \frac{1}{3} C_3 - \frac{4}{9} C_4 - \frac{20}{3} C_5 - \frac{80}{9} C_6, \\ C_9^{\text{eff}} &= \frac{4\pi}{\alpha_s} C_9 + Y(\hat{s}), \\ C_{10}^{\text{eff}} &= \frac{4\pi}{\alpha_s} C_{10}, \end{aligned} \quad (3)$$

where the perturbative part $Y(q^2)$ stands for the matrix element of four-quark operators and is given by

$$\begin{aligned}
Y(q^2) = & h(\hat{m}_c, \hat{s}) \left(\frac{4}{3}C_1 + C_2 + 6C_3 + 60C_5 \right) \\
& + \frac{1}{2}h(1, \hat{s}) \left(-7C_3 - \frac{4}{3}C_4 - 76C_5 - \frac{64}{3}C_6 \right) \\
& + \frac{1}{2}h(0, \hat{s}) \left(-C_3 - \frac{4}{3}C_4 - 16C_5 - \frac{64}{3}C_6 \right) \\
& + \frac{4}{3}C_3 + \frac{64}{9}C_5 + \frac{64}{27}C_6.
\end{aligned} \tag{4}$$

with $\hat{s} = q^2/m_{B_c}^2$, $\hat{m}_c = m_c/m_{B_c}$. We have neglected the resonance contribution. For the detailed discussion of such resonance effects, we refer to Refs. [9–11].

Exclusive decay $B_c \rightarrow D_s^* \mu^+ \mu^-$ is described in terms of matrix elements of the quark operators in the effective Hamiltonian over meson states, which can be parameterized in terms of form factors. The matrix elements of $B_c \rightarrow D_s^*$ transition are given by [34]

$$\begin{aligned}
\langle D_s^*(p) | (V - A)_\mu | B_c(p_{B_c}) \rangle = & -i\epsilon_\mu^*(m_{B_c} + m_{D_s^*})A_0(s) + i(p_{B_c} + p)_\mu(\epsilon^* p_{B_c}) \frac{A_+(s)}{m_{B_c} + m_{D_s^*}} \\
& + iq_\mu(\epsilon^* p_{B_c}) \frac{2m_{D_s^*}}{s} A_-(s) + \epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu} p_{B_c}^\rho p^\sigma \frac{2A_V(s)}{m_{B_c} + m_{D_s^*}}.
\end{aligned} \tag{5}$$

and

$$\begin{aligned}
\langle D_s^*(p) | \bar{s} \sigma_{\mu\nu} q^\nu (1 + \gamma_5) b | B_c(p_{B_c}) \rangle = & i\epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu} p_{B_c}^\rho p^\sigma 2T_1(s) \\
& + T_2(s) \left\{ \epsilon_\mu^*(m_{B_c}^2 - m_{D_s^*}^2) - (\epsilon^* p_{B_c}) (p_{B_c} + p)_\mu \right\} \\
& + T_3(s) (\epsilon^* p_{B_c}) \left\{ q_\mu - \frac{s}{m_{B_c}^2 - m_{D_s^*}^2} (p_{B_c} + p)_\mu \right\}
\end{aligned} \tag{6}$$

here $s = q^2$, $q_\mu = (p_{B_c} - p)_\mu$, and ϵ_μ is polarization vector of the vector meson D_s^* .

The dilepton invariant mass spectrum for $B_c \rightarrow D_s^* l^+ l^-$ decays can be expressed by [34, 35]

$$\frac{d\Gamma}{d\hat{s}} = \frac{G_F^2 \alpha^2 m_{B_c}^5}{2^{10} \pi^5} |V_{ts}^* V_{tb}|^2 \hat{u}(\hat{s}) D \tag{7}$$

where the explicit expression of D is

$$\begin{aligned}
D = & \frac{|A|^2}{3} \hat{s} \lambda (1 + 2 \frac{\hat{m}_l^2}{\hat{s}}) + |E|^2 \hat{s} \frac{\hat{u}(\hat{s})^2}{3} \\
& + \frac{1}{4 \hat{m}_{D_s^*}^2} \left[|B|^2 (\lambda - \frac{\hat{u}(\hat{s})^2}{3} + 8 \hat{m}_{D_s^*}^2 (\hat{s} + 2 \hat{m}_l^2)) + |F|^2 (\lambda - \frac{\hat{u}(\hat{s})^2}{3} + 8 \hat{m}_{D_s^*}^2 (\hat{s} - 4 \hat{m}_l^2)) \right] \\
& + \frac{\lambda}{4 \hat{m}_{D_s^*}^2} \left[|C|^2 (\lambda - \frac{\hat{u}(\hat{s})^2}{3}) + |G|^2 \left(\lambda - \frac{\hat{u}(\hat{s})^2}{3} + 4 \hat{m}_l^2 (2 + 2 \hat{m}_{D_s^*}^2 - \hat{s}) \right) \right] \\
& - \frac{1}{2 \hat{m}_{D_s^*}^2} \left[\text{Re}(BC^*) (\lambda - \frac{\hat{u}(\hat{s})^2}{3}) (1 - \hat{m}_{D_s^*}^2 - \hat{s}) \right. \\
& \left. + \text{Re}(FG^*) ((\lambda - \frac{\hat{u}(\hat{s})^2}{3}) (1 - \hat{m}_{D_s^*}^2 - \hat{s}) + 4 \hat{m}_l^2 \lambda) \right] \\
& - 2 \frac{\hat{m}_l^2}{\hat{m}_{D_s^*}^2} \lambda [\text{Re}(FH^*) - \text{Re}(GH^*) (1 - \hat{m}_{D_s^*}^2)] + \frac{\hat{m}_l^2}{\hat{m}_{D_s^*}^2} \hat{s} \lambda |H|^2, \tag{8}
\end{aligned}$$

with $\hat{m}_l = m_l/m_{B_c}$, and $\hat{m}_{D_s^*} = m_{D_s^*}/m_{B_c}$. The kinematic variables \hat{s} and \hat{u} are the same as Ref. [34]. The auxiliary functions A, B, C, E, F and G which are combinations of the effective Wilson coefficients in Eq. (3) and the form factors of $B_c \rightarrow D_s^*$ transition can be found in Refs. [34, 35]. For the convenience of the reader, we present these functions in the Appendix A.

The normalized forward-backward asymmetry (FBA) is defined as

$$\mathcal{A}_{FB}(\hat{s}) = \int d\hat{s} \frac{\int_{-1}^{+1} d\cos\theta \frac{d^2 Br}{d\hat{s} d\cos\theta} \text{Sign}(\cos\theta)}{\int_{-1}^{+1} d\cos\theta \frac{d^2 Br}{d\hat{s} d\cos\theta}}. \tag{9}$$

According to this definition, the explicit expression of FBA is:

$$\frac{d\mathcal{A}_{FB}}{d\hat{s}} D = \hat{u}(\hat{s}) \hat{s} [\text{Re}(BE^*) + \text{Re}(AF^*)]. \tag{10}$$

The lepton polarization can be defined as:

$$\frac{d\Gamma(\hat{n})}{d\hat{s}} = \frac{1}{2} \left(\frac{d\Gamma}{d\hat{s}} \right)_0 [1 + (P_L \hat{e}_L + P_N \hat{e}_N + P_T \hat{e}_T) \cdot \hat{n}] \tag{11}$$

where the subscript "0" stands for the unpolarized decay case. P_L and P_T are the longitudinal and transverse polarization asymmetries in the decay plane respectively, and P_N is the normal polarization asymmetry in the direction perpendicular to the decay plane.

The lepton polarization asymmetry P_i can be derived by

$$P_i(\hat{s}) = \frac{d\Gamma(\hat{n} = \hat{e}_i)/d\hat{s} - d\Gamma(\hat{n} = -\hat{e}_i)/d\hat{s}}{d\Gamma(\hat{n} = \hat{e}_i)/d\hat{s} + d\Gamma(\hat{n} = -\hat{e}_i)/d\hat{s}} \tag{12}$$

the results are

$$P_L D = \sqrt{1 - 4\frac{\hat{m}_l^2}{\hat{s}}} \left\{ \frac{2\hat{s}\lambda}{3} \text{Re}(AE^*) + \frac{(\lambda + 12\hat{s}\hat{m}_{D_s^*}^2)}{3\hat{m}_{D_s^*}^2} \text{Re}(BF^*) \right. \\ \left. - \frac{\lambda(1 - \hat{m}_{D_s^*}^2 - \hat{s})}{3\hat{m}_{D_s^*}^2} \text{Re}(BG^* + CF^*) + \frac{\lambda^2}{3\hat{m}_{D_s^*}^2} \text{Re}(CG^*) \right\}, \quad (13)$$

$$P_N D = \frac{-\pi\sqrt{\hat{s}}\hat{u}(\hat{s})}{4\hat{m}_{D_s^*}} \left\{ \frac{\hat{m}_l}{\hat{m}_{D_s^*}} [\text{Im}(FG^*)(1 + 3\hat{m}_{D_s^*}^2 - \hat{s}) \right. \\ \left. + \text{Im}(FH^*)(1 - \hat{m}_{D_s^*}^2 - \hat{s}) - \text{Im}(GH^*)\lambda \right. \\ \left. + 2\hat{m}_{D_s^*}\hat{m}_l[\text{Im}(BE^*) + \text{Im}(AF^*)] \right\}, \quad (14)$$

$$P_T D = \frac{\pi\sqrt{\lambda}\hat{m}_l}{4\sqrt{\hat{s}}} \left\{ 4\hat{s}\text{Re}(AB^*) + \frac{(1 - \hat{m}_{D_s^*}^2 - \hat{s})}{\hat{m}_{D_s^*}^2} [-\text{Re}(BF^*) + (1 - \hat{m}_{D_s^*}^2)\text{Re}(BG^*) + \hat{s}\text{Re}(BH^*)] \right. \\ \left. + \frac{\lambda}{\hat{m}_{D_s^*}^2} [\text{Re}(CF^*) - (1 - \hat{m}_{D_s^*}^2)\text{Re}(CG^*) - \hat{s}\text{Re}(CH^*)] \right\}. \quad (15)$$

In the family non-universal Z' model, the flavor neutral currents arise even at tree level owing to non-diagonal chiral coupling matrix. Postulating that the couplings of right-handed quark flavors with Z' boson are diagonal, the Z' part of the effective Hamiltonian for $b \rightarrow sl^+l^-$ transition is described by [24]

$$\mathcal{H}_{eff}^{Z'}(b \rightarrow sl^+l^-) = -\frac{2G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left[-\frac{B_{sb}^L B_{ll}^L}{V_{tb}V_{ts}^*} (\bar{s}b)_{V-A} (\bar{l}l)_{V-A} - \frac{B_{sb}^L B_{ll}^R}{V_{tb}V_{ts}^*} (\bar{s}b)_{V-A} (\bar{l}l)_{V+A} \right] + \text{h.c.} . \quad (16)$$

To extract the Z' corrections to the Wilson coefficients, one can reformulate Eq. (16) as

$$\mathcal{H}_{eff}^{Z'}(b \rightarrow sl^+l^-) = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* [\Delta C'_9 O_9 + \Delta C'_{10} O_{10}] + \text{h.c.} , \quad (17)$$

with

$$\Delta C'_9(M_W) = -\frac{g_s^2}{e^2} \frac{B_{sb}^L}{V_{ts}^* V_{tb}} S_{ll}^{LR} , \\ \Delta C'_{10}(M_W) = \frac{g_s^2}{e^2} \frac{B_{sb}^L}{V_{ts}^* V_{tb}} D_{ll}^{LR} . \quad (18)$$

where $S_{ll}^{LR} = (B_{ll}^L + B_{ll}^R)$, $D_{ll}^{LR} = (B_{ll}^L - B_{ll}^R)$ with B_{sb}^L and $B_{ll}^{L,R}$ referring to the effective chiral Z' couplings to quarks and leptons, respectively. The off-diagonal element B_{sb}^L contains a new weak phase and can be written as $|B_{sb}^L|e^{i\phi_s^L}$.

TABLE I: Default values of inputs parameters used in our numerical calculations.

$m_b = 4.8 \text{ GeV},$	$m_{B_c} = 6.28 \text{ GeV},$	$m_{D_s^*} = 2.112 \text{ GeV},$	$m_\mu = 0.106 \text{ GeV}$
$ V_{tb}V_{ts}^* = 0.041,$	$\alpha = 1/137,$	$\tau_{B_c} = 0.46 \times 10^{-12} s.$	

When we include the Z' contributions with the assumption of no significant RG running effects between $M_{Z'}$ and M_W scales, the Wilson coefficients can be written as

$$C_{9,10}^{SM}(M_W) \rightarrow C_{9,10}^{SM}(M_W) + \Delta C'_{9,10}(M_W). \quad (19)$$

After inclusion of the new contributions from Z' boson, the RG evolution of the Wilson coefficients down to low scale is exactly the same as in the SM.

III. NUMERICAL RESULTS

In this section, we focus on the numerical calculations of the branching ratios, forward-backward asymmetry and polarization asymmetries for $B_c \rightarrow D_s^* \mu^+ \mu^-$ decay. The input parameters which are related to our analysis are summarized in Table I.

For the form factors $A_V(s)$, $A_0(s)$, $A_+(s)$, $A_-(s)$, $T_1(s)$, $T_2(s)$ and $T_3(s)$, we choose them derived by the three-point QCD sum rules [20], in which the parametrization of the form factors with respect to q^2 are as follows:

$$F(q^2) = \frac{F(0)}{1 + \alpha \hat{s} + \beta \hat{s}^2}. \quad (20)$$

where the values of the parameters $F(0)$, α and β are listed in Table II.

TABLE II: $B_c \rightarrow D_s^*$ form factors in the QCD Sum Rules [20].

$F(q^2)$	$F(0)$	α	β
$A_V(q^2)$	0.54	-1.28	-0.230
$A_0(q^2)$	0.30	-0.13	-0.180
$A_+(q^2)$	0.36	-0.67	-0.066
$A_-(q^2)$	-0.57	-1.11	-0.140
$T_1(q^2)$	0.31	-1.28	-0.230
$T_2(q^2)$	0.33	-0.10	-0.097
$T_3(q^2)$	0.29	-0.91	0.007

In the family non-universal Z' model, the Z' contributions rely on four parameters $|B_{sb}^L|$, ϕ_s^L , $S_{\mu\mu}^{LR}$ and $D_{\mu\mu}^{LR}$. These parameters have been constrained from the well measured decays

TABLE III: The inputs parameters for the Z' couplings [25, 26].

	$ B_{sb}^L (\times 10^{-3})$	$\phi_s^L[^\circ]$	$S_{\mu\mu}^{LR}(\times 10^{-2})$	$D_{\mu\mu}^{LR}(\times 10^{-2})$
S1	1.09 ± 0.22	-72 ± 7	-2.8 ± 3.9	-6.7 ± 2.6
S2	2.20 ± 0.15	-82 ± 4	-1.2 ± 1.4	-2.5 ± 0.9

by many groups [24–27]. $|B_{sb}^L|$ and ϕ_s^L have been strictly constrained by $\bar{B}_s - B_s$ mixing, $B \rightarrow \pi K^{(*)}$ and ρK decays. After taking into account constraints from $\bar{B}_d \rightarrow X_s \mu\mu$, $K \mu\mu$ and $K^* \mu\mu$, as well as $B_s \rightarrow \mu\mu$ decays, the bounds on $S_{\mu\mu}^{LR}$ and $D_{\mu\mu}^{LR}$ are also obtained. For the sake of convenience, we recollect their numerical results in Table III, with S1 and S2 corresponding to two fitting results of UTfit Collaboration for $\bar{B}_s - B_s$ mixing [36].

Recently, CDF, D0, and LHCb collaborations [37–39] have updated the CP violation parameter ϕ_s in B_s system. These precise measurements will suppress the magnitude of $b - s - Z'$ coupling by about 10%, and have no effect on the new weak phase ϕ_s^L . However, the weak phase can be constrained by the data of $B \rightarrow \pi K^{(*)}$ and ρK decays and the results are consistent with the previous Refs. [25, 26]. Indeed, the quantity that is directly related to the decay studied here is the product of the couplings of $b - s - Z'$ and $\mu - \mu - Z'$, and the updated experimental data of B_s mixing have less effect on it. According to the above analysis, we will adopt the inputs parameters for the Z' couplings as in Table III in our theoretical calculation. Meanwhile, we also choose the extreme values of S1 which are named extreme limit values (ELV) to show the maximal effects of Z' contributions, and the ELV are

$$|B_{sb}^L| = 1.31 \times 10^{-3}, \phi_s^L = -79^\circ, S_{\mu\mu}^{LR} = -6.7 \times 10^{-2}, D_{\mu\mu}^{LR} = -9.3 \times 10^{-2}. \quad (21)$$

Using the input parameters given above, we obtain the results of the branching ratios both in the SM and the family non-universal Z' model without resonance contributions.

$$Br(B_c \rightarrow D_s^* \mu^+ \mu^-) = \begin{cases} 2.32_{-0.26}^{+0.27} \times 10^{-7} & (\text{SM}), \\ 3.36_{-0.35}^{+0.38} \times 10^{-7} & (\text{S1}), \\ 2.80_{-0.30}^{+0.32} \times 10^{-7} & (\text{S2}), \\ 5.21_{-0.54}^{+0.57} \times 10^{-7} & (\text{ELV}). \end{cases} \quad (22)$$

The theoretical errors are induced by the uncertainties of form factors. From the numerical results, one can see that branching ratio for decay $B_c \rightarrow D_s^* \mu^+ \mu^-$ is sensitive to the Z' contributions. With respect to the central value of the SM prediction, the new physics contributions in the family non-universal Z' model can provide an enhancement about 45%, 21%, and 125% for the case of S1, S2, and ELV, respectively.

Fig. 1 shows the \hat{s} dependence of the differential decay rates for decay $B_c \rightarrow D_s^* \mu^+ \mu^-$ both in the SM and the family non-universal Z' model using the central values of the

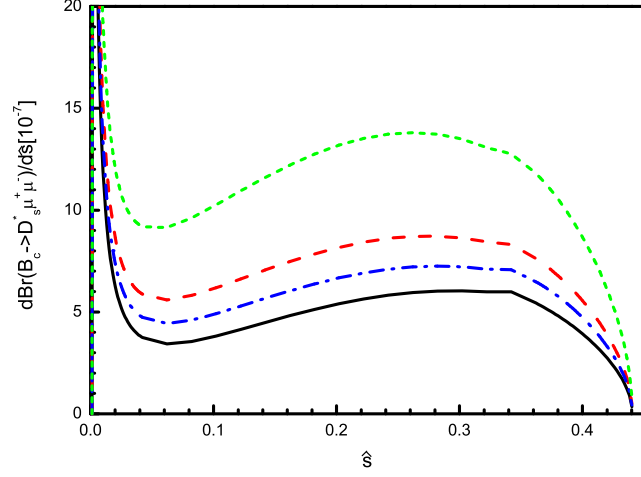


FIG. 1: The \hat{s} dependence of the differential decay rates $dBr(B_c \rightarrow D_s^* \mu^+ \mu^-)/d\hat{s}$ both in the SM and the family non-universal Z' model. The solid, dashed, dash-dotted, short-dashed lines show the SM prediction, the theoretical results of S1, S2, and ELV, respectively.

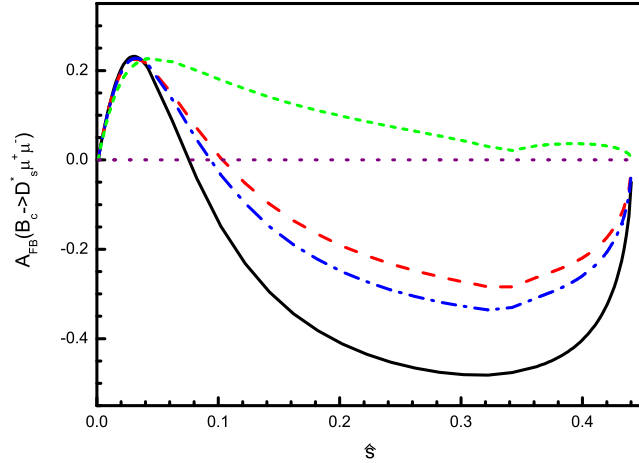


FIG. 2: The FBA of decay $B_c \rightarrow D_s^* \mu^+ \mu^-$ as a function \hat{s} both in the SM and the family non-universal Z' model.

input parameters. The solid line refers to the SM prediction, while the dashed, dash-dotted, short-dashed curves correspond to the theoretical results of S1, S2, and ELV, respectively. The Z' enhancements to the differential decay rate are significant in almost the whole region of \hat{s} and strongly depend on the variation of NP parameters.

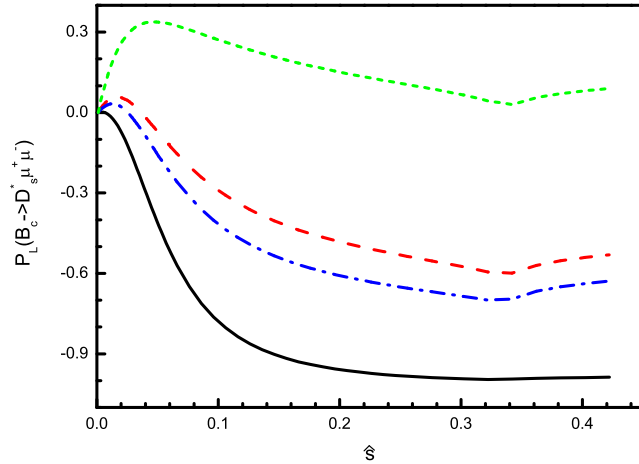


FIG. 3: The longitudinal lepton polarization asymmetry of decay $B_c \rightarrow D_s^* \mu^+ \mu^-$ as a function \hat{s} both in the SM and the family non-universal Z' model.

The \hat{s} dependence of forward-backward asymmetry for $B_c \rightarrow D_s^* \mu^+ \mu^-$ decay is presented in Fig. 2. Compared to the SM results, when including the NP effects from Z' boson, the FBA can be increased by about 47%, 38%, and 110% at most in S1, S2, and ELV, respectively. It is easy to see that the zero crossing in $A_{FB}(B_c \rightarrow D_s^* \mu^+ \mu^-)$ also exists and Z' corrections can shift $\hat{s}_0 = 0.075$ in the SM to $\hat{s}_0 = 0.104$ in S1, and $\hat{s}_0 = 0.093$ in S2, respectively. As for the case of ELV, the Z' effects on $A_{FB}(B_c \rightarrow D_s^* \mu^+ \mu^-)$ are more significant and can lead zero crossing to vanish.

In Fig. 3, we plot the longitudinal lepton polarization asymmetry of decay $B_c \rightarrow D_s^* \mu^+ \mu^-$ as a function \hat{s} both in the SM and the family non-universal Z' model. After inclusion of the Z' contributions, there are also apparent deviations in the values of the $P_L(B_c \rightarrow D_s^* \mu^+ \mu^-)$ for all the cases in Z' model from that of the SM predictions. When $\hat{s} > 0.08$, the value of the longitudinal polarization asymmetry can be changed from -1 in the SM to -0.5 in S1, and -0.6 in S2, respectively. In the extreme case, the Z' effects could flip the sign of the SM predictions when $\hat{s} > 0.006$ and the theoretical values might be close to zero in large momentum region.

The transverse lepton polarization asymmetry of decay $B_c \rightarrow D_s^* \mu^+ \mu^-$ as a function \hat{s} both in the SM and the family non-universal Z' model is given in Fig. 4. The new physics corrections from Z' boson are small, and will decrease the SM prediction about 25% for the cases of S1 and S2 in low \hat{s} region. However, for the case of ELV, the decrease could be rather large and reach 100% of the SM predictions. In addition, the sign of P_T will be changed in low momentum region and its values approach to zero when $\hat{s} > 0.037$.

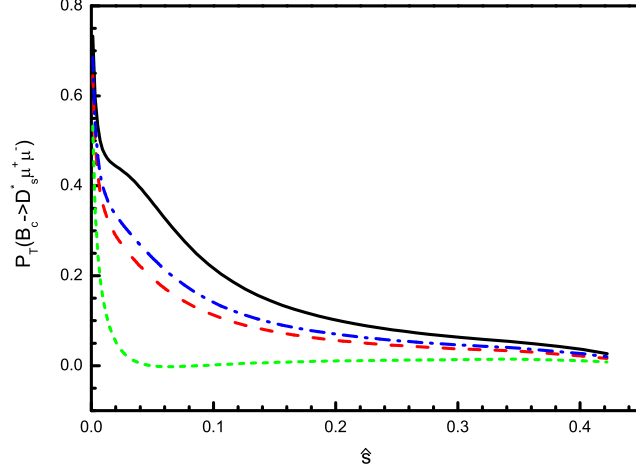


FIG. 4: The transverse lepton polarization asymmetry of decay $B_c \rightarrow D_s^* \mu^+ \mu^-$ as a function \hat{s} both in the SM and the family non-universal Z' model.

IV. SUMMARY

In this paper, we calculated the Z' contributions to the branching ratio, forward-backward asymmetry and polarization asymmetries for $B_c \rightarrow D_s^* \mu^+ \mu^-$ decay in the family non-universal Z' model by employing the effective Hamiltonian with the form factors calculated in the three-point QCD sum rules.

In Section 2, we presented the theoretical framework of $b \rightarrow sl^+l^-$ transition including the effective Hamiltonian, matrix element and the physical observables. In Section 3, we showed the numerical results of the observables and made phenomenological analysis for $B_c \rightarrow D_s^* \mu^+ \mu^-$ decay in the SM and the family non-universal Z' model.

As expected, the Z' contributions to the observables for $B_c \rightarrow D_s^* \mu^+ \mu^-$ decay could be significant in size. From the numerical results, we found that:

- With respect to the SM prediction, the Z' contributions to the differential decay rates are significant in almost the whole region of \hat{s} and strongly depend on the variation of NP parameters.
- The new physics enhancements to FBA could be large, and reach 47%, 38%, and 110% at most in S1, S2, and ELV, respectively. The zero crossing could be shifted from $\hat{s}_0 = 0.075$ in the SM to $\hat{s}_0 = 0.104$ in S1, and $\hat{s}_0 = 0.093$ in S2, respectively. As for the case of ELV, the Z' effects could lead zero crossing to vanish.
- The values of P_L deviated apparently from that of the SM predictions for all the

cases in Z' model. In high \hat{s} region, the values of P_L could be changed from -1 in the SM to -0.5 in S1, -0.6 in S2, and 0 in ELV, respectively.

- The new physics corrections to P_T would decrease the SM prediction about 25% for the cases of S1 and S2 in low \hat{s} region. However, for the case of ELV, the decrease could be rather large and reach 100% of the SM predictions.

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Appendix A: Auxiliary functions

The auxiliary functions are given as follows [34, 35]:

$$A(\hat{s}) = \frac{2}{1 + \hat{m}_{D_s^*}} \tilde{C}_9^{eff}(\hat{s}) A_V(\hat{s}) + \frac{4\hat{m}_b}{\hat{s}} \tilde{C}_7^{eff} T_1(\hat{s}), \quad (23)$$

$$B(\hat{s}) = (1 + \hat{m}_{D_s^*}) \tilde{C}_9^{eff}(\hat{s}) A_0(\hat{s}) + \frac{2\hat{m}_b}{\hat{s}} (1 - \hat{m}_{D_s^*}^2) \tilde{C}_7^{eff} T_2(\hat{s}), \quad (24)$$

$$C(\hat{s}) = \frac{1}{1 + \hat{m}_{D_s^*}} \tilde{C}_9^{eff}(\hat{s}) A_+(\hat{s}) + \frac{2\hat{m}_b}{1 - \hat{m}_{D_s^*}^2} \tilde{C}_7^{eff} \left(T_3(\hat{s}) + \frac{1 - \hat{m}_{D_s^*}^2}{\hat{s}} T_2(\hat{s}) \right), \quad (25)$$

$$E(\hat{s}) = \frac{2}{1 + \hat{m}_{D_s^*}} \tilde{C}_{10}^{eff} A_V(\hat{s}), \quad (26)$$

$$F(\hat{s}) = (1 + \hat{m}_{D_s^*}) \tilde{C}_{10}^{eff} A_0(\hat{s}), \quad (27)$$

$$G(\hat{s}) = \frac{1}{1 + \hat{m}_{D_s^*}} \tilde{C}_{10}^{eff} A_+(\hat{s}), \quad (28)$$

$$H(\hat{s}) = \frac{2\hat{m}_{D_s^*}}{\hat{s}} \tilde{C}_{10}^{eff} A_-(\hat{s}), \quad (29)$$

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- [1] M. S. Alam, et al., (CLEO Collaboration), Phys. Rev. Lett. **74** (1995) 2885.
[2] A. Ali, Int. J. Mod. Phys. **A 20** (2005) 5080, arXiv:0412128[hep-ph].
[3] F. Abe, et al., (CDF Collaboration), Phys. Rev. **D 58** (1998) 112004.
[4] N. Brambilla et al., (Quarkonium Working Group), CERN-2005-005, arXiv:0412158[hep-ph].

- [5] N. Brambilla et al., Eur. Phys. J. C **71** (2011) 1534, arXiv:1010.5827v3[hep-ph].
- [6] J. Sun, Y. Yang, W. Du and H. Ma, Phys. Rev. D **77** (2008) 114004.
- [7] M. P. Altarelli and F. Teubert, Int. J. Mod. Phys. A **23** (2008) 5117.
- [8] U. O. Yilmaz and G. Turan, Eur. Phys. J. C **51** (2007) 63.
- [9] A. Ahmed, I. Ahmed, M. Ali Paracha, et. al., arXiv:1108.1058v3.
- [10] I. Ahmed, M. Ali Paracha, M. Junaid, et. al., arXiv:1107.5694v2.
- [11] U. O. Yilmaz, arXiv:1204.1261v1.
- [12] C. Q. Geng, C.W. Hwang, and C. C. Liu, Phys. Rev. D **65** (2002) 094037.
- [13] A. Faessler, Th. Gutsche, M. A. Ivanov, J. G. Korner and V. E. Lyubovitskij, Eur. Phys. J. C **4** (2002) 18, arXiv:0205287[hep-ph].
- [14] D. Ebert, R. N. Faustov and V. O. Galkin, Phys. Rev. D **82**, 034032 (2010).
- [15] M. Ali Paracha, Ishtiaq Ahmed, M. Jamil Aslam, Phys. Rev. D **84** (2011) 035003, arXiv:1101.2323[hep-ph].
- [16] T. M. Aliev and M. Savci, Phys. Lett. B **434** (1998) 358, arXiv:9804407[hep-ph].
- [17] T. M. Aliev and M. Savci, G **24** (1998) 2223, arXiv:9805239[hep-ph].
- [18] T. M. Aliev and M. Savci, Eur. Phys. J. C **47** (2006) 413, arXiv:0601267[hep-ph].
- [19] K. Azizi and V. Bashiry, Phys. Rev. D **76** (2007) 114007.
- [20] K. Azizi, F. Falahati, V. Bashiry and S. M. Zebarjad, Phys. Rev. D **77**(2008) 114024, arXiv:0806.0583[hep-ph].
- [21] P. Langacker and M. Plümacher, Phys. Rev. D **62** (2000) 013006, arXiv:0001204[hep-ph].
- [22] V. Barger, C. W. Chiang, P. Langacker and H. S. Lee, Phys. Lett. B **598** (2004) 218, arXiv:0406126[hep-ph].
- [23] Q. Chang, X. Q. Li and Y. D. Yang, JHEP **0905** (2009) 056, arXiv:0903.0275[hep-ph].
- [24] V. Barger, L. Everett, J. Jiang, P. Langacker, T. Liu and C. Wagner, Phys. Rev. D **80** (2009) 055008, arXiv:0902.4507 [hep-ph]; JHEP **0912** (2009) 048, arXiv:0906.3745[hep-ph].
- [25] Q. Chang, X. Q. Li and Y. D. Yang, JHEP **1002** (2010) 082, arXiv:0907.4408[hep-ph].
- [26] Q. Chang, X. Q. Li and Y. D. Yang, JHEP **1004** (2010) 052, arXiv:1002.2758[hep-ph].
- [27] C. W. Chiang, R. H. Li and C. D. Lü, Chinese Physics C **36** (2012) 14, arXiv:0911.2399[hep-ph].
- [28] W. Altmannshofer, P. Ball, A. Bharucha, A. J. Buras, D. M. Straub and M. Wick, JHEP **0901** (2009) 019, arXiv:0811.1214[hep-ph].
- [29] K. G. Chetyrkin, M. Misiak and M. Munz, Phys. Lett. B **400** (1997) 206 [Erratum-ibid. B **425** (1998) 414], arXiv:9612313[hep-ph].
- [30] M. Beneke, T. Feldmann and D. Seidel, Nucl. Phys. B **612** (2001) 25, arXiv:0106067[hep-ph].
- [31] C. Bobeth, M. Misiak and J. Urban, Nucl. Phys. B **574** (2000) 291, arXiv:9910220[hep-ph].
- [32] C. Bobeth, A. J. Buras, F. Krüger and J. Urban, Nucl. Phys. B **630** (2002) 87, arXiv:0112305[hep-ph].

- [33] T. Huber, E. Lunghi, M. Misiak and D. Wyler, Nucl. Phys. **B 740** (2006) 105, arXiv:0512066[hep-ph].
- [34] A. Ali, P. Ball, L. T. Handoko, and G.Hiller, Phys. Rev. **D 61** (2000) 074024.
- [35] Wen-Jun Li, Yuan-Ben Dai, and Chao-Shang Huang, Eur. Phys. J. **C 40** (2005) 565, arXiv:0410317[hep-ph].
- [36] M. Bona *et al.*, arXiv:0906.0953[hep-ph]; M. Bona *et al.* (UTfit Collaboration) PMC Phys. **A 3** (2009) 6, arXiv:0803.0659[hep-ph]; online update at: <http://www.utfit.org/UTfit/Results>.
- [37] (CDF Collaboration), CDF public note 10778.
- [38] V. M. Abazov, et al., (D0 Collaboration), Phys. Rev. **D 85** (2012) 032006.
- [39] R. Aaij, et al., (LHCb Collaboration), Phys. Lett. **B 707** (2012) 497.